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Control of Near-wall Coherent Structure Formation for Drag Reduction in Turbulent Boundary Layers

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Abstract
Using direct numerical simulations of turbulent channel flow, we present a new method for skin friction reduction by prevention of streamwise vortex formation near the wall. Based on recent evidence of streak instability-induced vortex generation, we develop a new technique for drag reduction, enabling large-scale flow forcing without requiring instantaneous flow information. As proof-of-principle, x-independent forcing, with a wavelength of 400 wall units and an amplitude of only 6% of the centerline velocity, produces a significant sustained drag reduction: 20% for imposed counterrotating streamwise vortices and 50% for colliding, z-directed wall jets. The drag reduction results from weakened longitudinal vortices near the wall, due to forcing-induced suppression of the underlying streak instability. In particular, the forcing significantly weakens the wall-normal vorticity flanking lifted low-speed streaks, thereby arresting the streaks' instability responsible for vortex generation. These results suggest promising new drag reduction strategies, e.g. passive vortex generators or colliding spanwise jets from x-aligned slots, involving large-scale (hence more durable) actuation and requiring no wall sensors or control logic.

Objectives
Streamwise vortices are now known to dominate near-wall turbulence production and transport, but their physical nature poses some formidable obstacles: (i) small dominant lengthscales (O(0.1 mm) for aircraft), (ii) random (x,z) locations, and (iii) apparently complex spatiotemporal dynamics. The most logical approach to CS-based reduction of drag and heat transfer is to simply prevent vortex formation in the first place (in contrast to many approaches which counteract the wall interaction of fully developed CS). It has long been hypothesized that a major source of turbulence production near the wall is the instability of inflectional low-speed streaks (*e.g.* [1-2]), although most details still remain unresolved. In particular, the following key issues have yet to be addressed in detail: (i) the relationship between streak instability and the formation mechanism of longitudinal vortices, (ii) physical space (3D) vortex dynamics arising from streak instability, and (iii) streak instability control strategies aimed at drag reduction.

As an alternative to popular microscale control approaches, our objective nere is to investigate a new large-scale control approach explicitly designed to disrupt the naturally occurring vortex regeneration mechanism. We investigate CS suppression through large-scale manipulation of streak instability, and explain the observed control effect using

instability and vortex dynamics concepts. For additional details of our drag reduction approach, the reader is referred to Schoppa & Hussain[5].

Computational Approach

In the following, we address vortex regeneration and its control using direct numerical simulations of the Navier-Stokes equations. Periodic boundary conditions are used in x and z, and the no-slip condition is applied on the two walls normal to y; see *Kim et al.*[6] for the simulation algorithm details. The control simulations are initialized with full-domain channel flow turbulence at Re=1800 and 3200[6], with 48x65x48 and 192x129x192 dealiased Fourier modes respectively. Actuation is represented by an applied control flow, either maintained at a constant amplitude or allowed to freely evolve, superimposed onto the turbulence.

Results & Discussion

In the following, we investigate drag reduction by: (i) a spanwise row of counter-rotating, x-independent streamwise vortices, centered in the outer region (at the channel centerline) and (ii) x-independent, z-directed colliding wall jets. As a simple model of streamwise vortex generators or spanwise slot jets, we consider a control flow of the form

$$U_{con}=0$$
$$V_{con}(y,z)=-A\beta\cos(\beta z)(1+\cos\pi(y/h-1))$$
$$W_{con}(y,z)=-A\pi\sin(\beta z)\sin\pi(y/h-1), \qquad (1)$$

which satisfies the continuity equation and the no-slip condition on the channel walls (at y=0,2h), where A is the control amplitude and $2\pi/\beta^+\cong400$. To demonstrate proof-of-principle for large-scale forcing, the z wavelength of the control flow is four times the characteristic streak spacing of approximately 100 wall units; even much larger-scale control (although computationally prohibitive) may be possible in practice. As illustrated in Fig. 1(a), the control flow (1) has a much larger scale than local minima of $u(y,z)$ near the wall, representing lifted low-speed streaks. For simplicity, we focus on the lower half of the channel (i.e. $y\in[0,h]$) in this and other figures; the upper half yields similar results. For a full period in z, (1) represents an array of counter-rotating 2D streamwise vortices (Fig. 1a), termed *vortex control.* Over the half period $\beta z\in[\pi/2,3\pi/2]$, (1) resembles colliding, spanwise-directed 2D wall jets (region *WJ* in Fig. 1a), referred to as *wall jet control.* Thus, we actually simulate a single control flow, distinguishing vortex and wall jet control by the region of z considered. In practice, the relative extents of diverging (outside *WJ*) and converging (inside *WJ*) wall jets can be adjusted to reduce the former.

To assess potential drag reduction, the time evolution of wall-integrated shear is shown in Fig. 2 for several control cases. For both, we consider two methods of forcing: (i) *free* forcing in which the control flow (1) is superimposed onto a turbulent flowfield at t_0=0 and allowed to freely evolve, and (ii) *frozen* forcing with the x-mean Fourier coefficients of the control flow maintained constant in time. For frozen forcing, V_{con} and W_{con} are specified as the flowfield resulting after one turnover time of viscous, 2D evolution of the initial condition (1).

Significantly, Fig. 2 reveals that substantial drag reduction, sustained in time for frozen forcing, is attainable – 20% for vortex control and 50% for wall jet control. In both

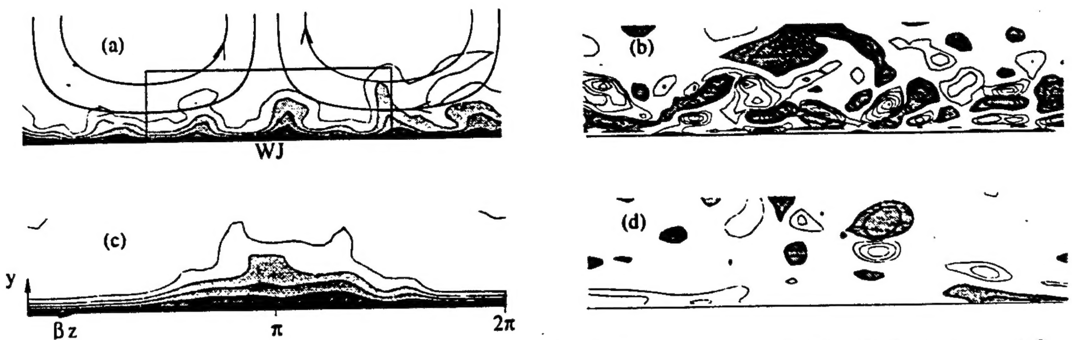

Figure 1. Distributions of $u(y,z)$ in (a,c) and $\omega_x(y,z)$ in (b,d) near one wall of turbulent channel flow at Re=1800, without (a,b) and with (c,d) an imposed large-scale control flow. The controlled flows, shown at t_0^+=500 (after control starts), have a frozen forcing amplitude of 6%. Note the disruption of streaks and the attenuation of streamwise vortices near the wall by control.

cases, a surprisingly weak control amplitude of 6% (i.e. $V_{con}|_{max}=2A\beta=0.06U_c$) is most effective, in general desirable from the practical standpoint of low power consumption (active control) or parasitic drag (passive control) of actuators. The dependence of drag on the (frozen) forcing amplitude (not shown) indicates a cusp-like effect of the control amplitude; the control effect is insignificant for 2% and weaker forcing, while 15% and stronger forcing leads to increased drag for both vortex and wall jet control. The increased drag at higher amplitudes reflect direct generation of drag by the control flow itself, occurring even in the absence of background turbulence. The optimum control is attained when the control is strong enough to stabilize near-wall streaks (discussed below), yet weak enough not to induce significant additional drag. Significant drag reduction is also observed for free forcing, at both Re=1800 and 3200 (Fig. 2). Although the control effect is temporary for free forcing, due to eventual dissipation of the control flow, significant drag reduction is observed for O(1000) wall time units. During this time, the control flow advects $(U_c^+)(\Delta t^+)$~16,000 wall units downstream, thus suggesting the practical feasibility of large-scale, effective control in both x and z (i.e. simultaneously many streaks, covering numerous wall vortices).

To understand these observed drag reduction phenomena, we first consider the control effect on lifted streaks, visualized in Figs. 1(a,c) by $u(y,z)$ before and after control (at t_0^+=500). The numerous preexisting lifted streaks (Fig. 1a) are flattened by splatting where V_{con} pushes fluid toward the wall and W_{con} spreads it in z (outside of WJ). Within the wall jet control region WJ, V_{con} is directed away from the wall and W_{con} converges in z, causing cross-diffusion of compressed streaks and hence weakening ω_y. Along the entire wall, even very weak control drastically decreases the ω_y originally flanking streaks in the uncontrolled flow (cf. Figs. 1a,c). The significance of this attenuation of ω_y lies in our recent results regarding formation of new streamwise vortices near the wall by streak instability[4], when ω_y is above a threshold. Most importantly for control, we find that sufficient ω_y flanking streaks is required for instability and that the instability growth rate increases significantly with the ω_y magnitude (Fig. 3). The growth rate data in Fig. 3 are for sinuous instability modes (i.e. z displacement of streaks, with sinusoidal x variation)

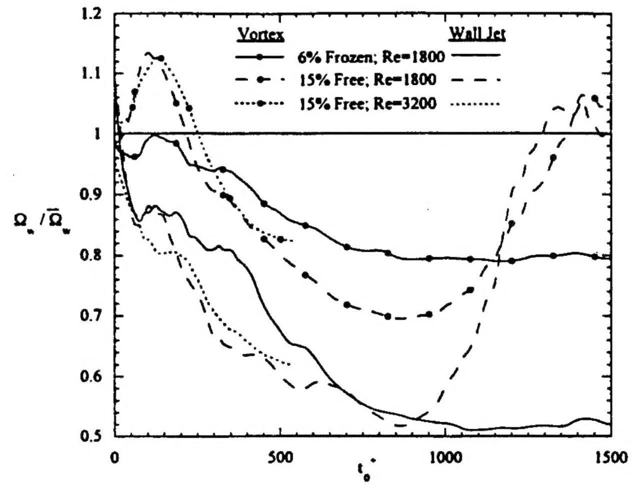

Figure 2. Time evolution of wall-integrated shear stress (normalized by the time-mean of the uncontrolled flow), illustrating significant drag reduction by large-scale control.

of the base flow family

$$U(y,z)=U_0(y)+(\Delta u/2)\cos(4\beta z)\, y \exp(-\sigma y^2);$$
$$V=W=0\,, \tag{2}$$

where $U_0(y)$ is the mean velocity. The spanwise wavenumber of 4β corresponds to a streak spacing of 100 wall units, and the parameter σ is specified so that the maximum streak ω_y, with normal circulation Δu, occurs at $y^+=30$. The base flow (2) is found to be an accurate representation of vortex-free low-speed streaks[4] (i.e. during the quiescent phase of regeneration) observed in uncontrolled near-wall turbulence.

In essence, both vortex and wall jet control break the near-wall vortex regeneration cycle by disrupting the naturally occurring (unstable) distributions of streaks generated by previous or preexisting streamwise vortices. Recalling the necessity of sufficient streak ω_y for instability (Fig. 3) and hence vortex formation, the reduction of local streak ω_y peaks by control is expected to significantly attenuate near-wall streamwise vortex formation. A comparison of the near-wall ω_x with and without control (Figs. 1b,d) indicates that this is indeed the case. Without control (Fig. 1b), numerous compact, drag-producing vortices with strong ω_x are present immediately near the wall. In contrast, the reduction of ω_y across streaks by control significantly weakens ω_x in the controlled flow (Fig. 1d), with no compact vortices present near the wall. Statistics of ω_y' confirm a strong reduction of local ω_y maxima by control, accompanied by large suppression of ω_x' and drag-producing v' (Fig. 4). The latter occurs only after existing vortices, which eventually weaken by annihilation due to cross-diffusion and dissipate, are not replaced by equally strong and numerous vortices, due to the suppressed vortex formation mechanism by control-induced streak ω_y reduction.

Since streamwise vortex formation and the associated enhanced drag appear to be reliant on lifted low-speed streaks with strong ω_y, large-scale (relative to the natural streak spacing) control of streaks is a potentially effective approach to drag reduction. We demonstrate here the feasibility of drag reduction via bulk forcing using either counter-

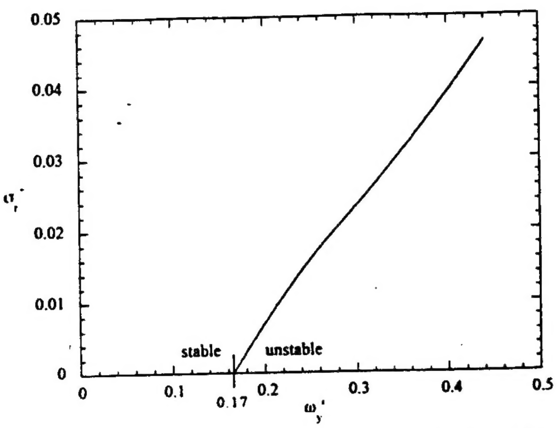

Figure 3. Dependence of sinuous streak instability growth rate σ_r^+ on the streaks' ω_y', for the base flow (2).

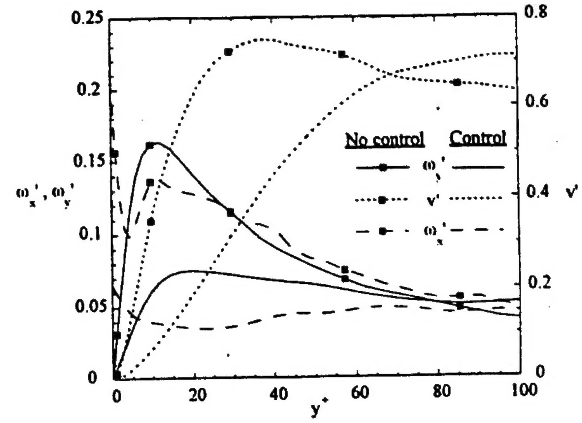

Figure 4. Suppression of v', ω_x', and ω_y' by large-scale control at t_0^+=500, with Re=1800 and frozen 6% forcing.

rotating vortex generators or colliding spanwise wall jets, requiring no instantaneous flow information (otherwise necessary for adaptive control). For implementation at very high Re, the physical scale of our control will likely decrease, but being significantly larger than the near-wall structures, will surely alleviate the micro-scale requirement for controllers and eliminate the need for sensors.

Future Plans

Based on these promising preliminary results, we propose a series of "numerical experiments" for the forthcoming year of support to better understand this drag reduction phenomenon and to assess potential implementation strategies. In particular, we plan to analyze the viscous annhilation of streaks (i.e. a type of planar reconnection) brought about by control, in order to optimize the streak-stabilization effect. Furthermore, computations in larger z-domains (~1000 wall units, covering 10 streak widths) and at higher Re (~5000) will be carried out to quantify the effectiveness of very large-scale control and to ascertain possible low-Re effects. Finally, alternative control implementations will be investigated, including spanwise wall jets and near-wall control vortices generated by wall boundary condition manipulation (to mimic near-wall slot injection), for comparison with our current results for superimposed volumetric control.

We also propose to develop a low-order model of the near-wall region to control skin friction and heat transfer. In this, we use a new basis consisting of eigenfunctions of the nonlinear instability problem and develop amplitude equations describing chaotic dynamics. Further, we find matching boundary conditions at the outer edge of the buffer layer for LES and higher-Re DNS studies.

For possible future experimental studies, one promising implementation of our drag reduction approach consists of an array of large-scale control devices, *i.e.* S_x and S_z in Fig. 5 much larger than the characteristic near-wall flow lengthscale of O(0.1 mm), say O(10 cm) if feasible. No sensors for flow measurement or electronic control hardware are necessary. Two possible embodiments for the control device are: (1) wall-mounted vortex generators, and (2) spanwise-directed, colliding wall jets. Embodiment (1) involves wall-mounted tabs at a slight angle θ to the flow direction, designed to produce

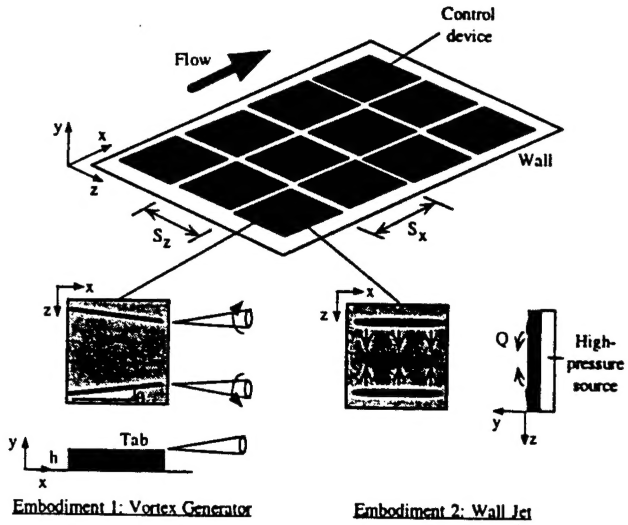

Figure 5. Schematic of large-scale drag reduction strategies, illustrating vortex and spanwise wall jet embodiments.

long, streamwise-aligned control vortices. Computational results indicate that a very small control vortex circulation is optimum; thus a small tab angle θ and hence little additional parasitic drag will be involved. Embodiment (2) involves wall jets issued from narrow, streamwise slots in the wall, driven by an external volume flowrate Q (Fig. 5). Slots neighboring in z are oriented so that adjacent wall jets collide to produce an upwelling (*i.e.* normal to the wall) control flow (Fig. 5), as modeled by region *WJ* in our computations (Fig. 1a). In practice, the relative extents of diverging (outside *WJ*) and converging (inside *WJ*) wall jets can be adjusted to reduce the former, noting that the converging wall jet region produces the largest drag reduction.

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